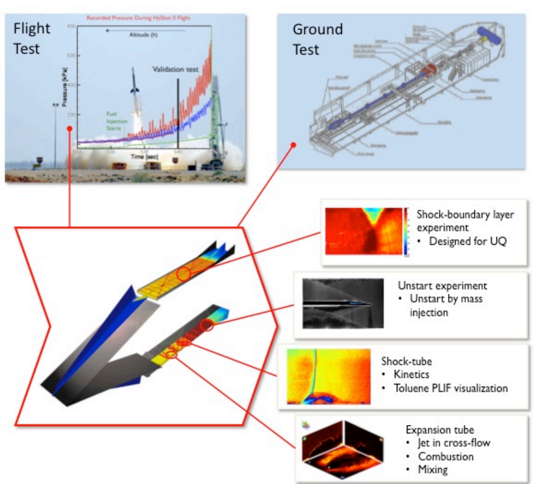
The PSAAP Center at Stanford

http://psaap.stanford.edu

The mission of the PSAAP Center at Stanford is to build and demonstrate computational capabilities for the simulations of supersonic combustion engines (scramjet) of hypersonic air-breathing vehicles. The emphasis of the Center is to evaluate the operability limit of the scramjet as the fuel flow rate is increased. Thermal choking, flow separation and flame blow-off are phenomena that can lead to dramatic loss of performance; simulations are critical to achieve safe operation without over-conservative design. Unstart events - generally defined as conditions leading to subsonic flow in the engine – serve as indicators of the system failure and lead to the identification of the allowable operability range.

Faculty from five Departements in the School of Engineering at Stanford are involved in the project together with colleagues from University of Michigan and SUNY StonyBrook.

The Center is developing multiphysics computational tools that, combined with an uncertainty quantification framework, allow evaluating the scramjet performance. Quantification of Margins and Uncertainties (QMU) provides the rationale for the analysis. In QMU a metric that characterizes the performance is monitored as a function of the design parameter - the fuel flow rate - within the expected operating scenario. The occurrence of unstart leads to the identification of safety factors that account for all the uncertainty present while providing a user-specified margin. The other fundamental tool formulated at the Center is a computation-management tool (namely Ray), which formally quantifies numerical errors and uncertainties to balance the efforts required to achieve a specified level of confidence in the predictions.

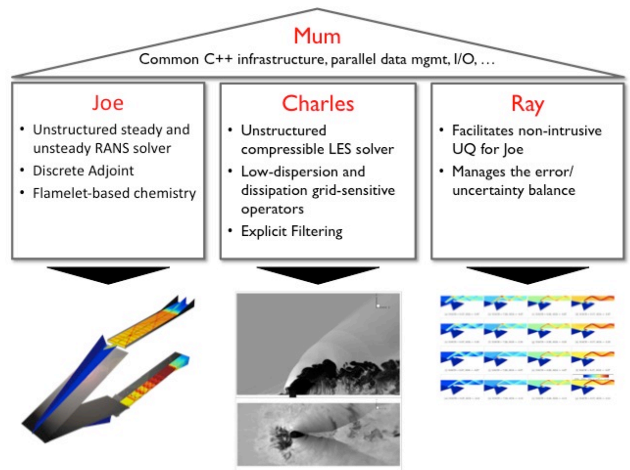


The successful flight of the HyShot II vehicle in 2002 provides a reference case to evaluate the accuracy of the computations framework developed at the Center. Although the vehicle did not operate close to the unstart limit, the available data collected in flight form a unique validation test. Moreover, the inherent uncertainty in the flight conditions due to a failure of the telemetry system, and the limited amount of measurements, provide a challenging scenario for validation. Complementary full-system experimental studies in land-based facilities (at DLR in Germany) are also extensively used at the Center to provide additional validation. Finally, several small-scale experiments carried out at Stanford provide single-physics validation data useful to assess the accuracy of the models used in the computations.

Recent discussion with the AirForce Research Laboratory has also lead to interest in the HiFire II program, a hydrocarbon-powered hypersonic vehicle expected to fly later in the year. The availability of extensive experimental data and detailed analysis of the operating range create an opportunity for a critical evaluation of the Center predictive ability.

The Center research is organized around several integrated groups. Two of them are responsible for the development of the simulation framework and the uncertainty quantification methodology, respectively. The other five groups address one of the physics component of the system: i) shock dynamics, ii) mixing and combustion, iii) fuel injection, iv) thermal management, v) flight condition inference.

The simulation framework is based on novel computational tools developed in house from the experience gained in the previous NNSA Center at Stanford. Specifically a common C++/MPI infrastructure (Mum) is deployed to solve the time-dependent compressible, reacting flow equations on 3D unstructured grids. Both turbulence modeling (RANS) and turbulence resolving (LES) simulations can be carried out and various levels of closure can be employed. Likewise, the heat release from combustion in the scramjet can be evaluated using multiple-fidelity models ranging from a purely empirical law to a sophisticated flamelet/progress variable approach, which includes detailed representation of the chemical kinetic process. The full system analysis are carried out using RANS-type closure (the Joe code) whereas the high-fidelity simulations (the charLES code) are typically employed for subsystem analysis to guide the evaluation and further refinement of RANS models.



Discrete adjoint operators are built in the code and used mainly to drive grid refinement and provide discretization error estimates for the error/uncertainty balance (the Ray code).

A unique component of the PSAAP Center at Stanford is the strong collaboration with the Computer Science Dept. Along with the the center's software architects/developers, the group is designing a domain-specific language (DSL) for mesh-based PDEs, and demonstrating how domain knowledge can allow a single version of a flow solver to map efficiently to a variety of different computer architectures, including multicore and GPU.

The goal of the uncertainty quantification (UQ) group is to define the theoretical framework for applying the QMU analysis and to develop and deploy the algorithms that enable the computations under uncertainty. Efforts on propagating aleatory uncertainty (natural variability) have lead to the introduction of a novel, non-intrusive simplex-based algorithm that has proved extremely effective. Ongoing work is focused on a practical framework to characterize epistemic (model-form) uncertainty, which is defined in terms of intervals. Strong emphasis has also been posed on the formulation of the error/uncertainty balance that enables a rationale allocation of computational resources.

The five physics groups carry out two main tasks: the first is to perform detailed validation of the different physical aspects of the scramjet, the second is to identify the uncertainties associated to each component of the full system. These groups are strongly integrated with experimentalists who are either involved in small-scale tests at Stanford or help assessing and interpreting measurements available from other sources.

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References

"A QMU approach for characterizing the operability limits of air-breathing hypersonic vehicles" RESS, 2010.

"Numerical Predictions of the Performance in Flight of an Air-Breathing Hypersonic Vehicle" ASME-2010-40186, 2010.

"Risk Assessment of Hypersonic Flow Simulations Using Adjoint-Based Sampling Methods" AIAA-2010-2921, 2010.